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OFFICE OF AEROSPACE RESEARCH

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19

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JAN NASILOWSKI

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Abstract

This report presents an idea for the uniform description of phenomena associated with electrical explosion of wires and electric fuses, based upon the fact of disintegration of wires into parts with definite spacing. In particular, observations concerned with pre-arcing energy, cutoff currents, peak voltages, and current pause are explained.

Contents

Illustrations

Tables

Chain of Arcs as a Determining Factor in Explosion of Wires

I. INTRODUCTION

In recent years, research has revealed that the process of destruction of a wire by short-circuited currents cannot be treated as uniform heating and evaporation of the wire adiabatically (Chace and Moore, 1959). In reality, the wire gets torn to pieces, probably under the influence of magneto-thermo-elastic forces (Hryniczuk), and arcing occurs between the separate segments (Wrana, 1939; Nasilowski; Baxter, 1962; and Barrington, 1956). Up until now, research has made it possible to calculate the expected number of short arcs for the case of a wire disintegrating into drops, or for the disintegration of a wire surrounded by sand into segments, resulting in the so-called striated disintegration.

The development of future research will depend mostly upon the creation of a general hypothesis that will explain simultaneously a large number of effects, each of which is now explained by a different theory, explained only partially, or not explained at all.

There exists a justified basis for belief that the effects resulting from the explosion – such as pre-arcing energy, cutoff current, and current pause – depend upon the number of arcing breaks in the fuse wire as well as their rate of formation. This assumption permits one to make a hypothesis useful for judgment and prediction of results of physical experiments, as well as for testing of fuses, which

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are undoubtedly the oldest technological application of this phenomenon. The physical processes which occur in fuses are the same as those which occur in only recently-discovered applications of exploding wires.

2. PROBLEM OF PRE-ARCING ENERGY

According to authors interested in the disintegration of wires as applicable to fuses during the pre-arcing period, the total energy supplied to a fuse is at most that energy necessary to raise the temperature of the wire to its melting point with the eventual partial absorption of energy by the melting of the metal (Baxter, 1962; Barrington, 1956; and Lucchi, 1949).

Different authors who have studied the phenomenon of destruction of wire with sharp rise times in current, report that during the pre-arcing period it is possible to deliver more energy to the wire than is needed to melt or even evaporate completely the whole mass of wire (Chace and Moore, 1959; Wrana, 1939; Barrington, 1956; Kvartskhava, 1956; and Keilhacker, 1960).

Here, the inconsistency is so large that it cannot be blamed upon experimental errors. One must therefore assume that the process of destruction of wire by the current is not a simple sequence of phase transitions of a metal being heated by the current.

The results described above can be explained if one takes into consideration the fact that breaks form in the wire and hamper the flow of energy to the rest of the fuse wire by stopping the current flow. The total energy delivered to the fuse wire during the pre-arcing period can be considered to be the result of competition between two phenomena (Nasilowski, 1961):

(1) Rapid increase in current which causes heating of the wire and its disintegration.

(2) Break-up of the wire into pieces as a purely mechanical phenomenon, which, once begun, is to some degree independent of the current which caused it.

If the current does not increase too quickly (10^4 to 10^6 amp/sec) then the break-up of the wire into segments will succeed in preventing the flow of energy to the rest of the wire before too much of it gets there. In such a case, the average temperature of the wire during its disintegration might even be less than the melting temperature (Barrington, 1956).

However, when the current grows very quickly (10^7 to 10^9 amp/sec) which is usual in experiments where the current sources are high-voltage capacitors with negligible inductance, then the flow of energy is no longer limited by the regular formation of the breaks in the wire. Hence one can deliver more energy to the wire than is needed to melt all of the mass of the wire (Keilhacker, 1960). Thus before the fuse wire loses its mechanical continuity, its mass may absorb more energy than the amount needed to melt or even evaporate the wire, provided that the rate of energy transfer is sufficiently high; this means a fast rise time of the short-circuited current.

3. PROBLEM OF CUTOFF CURRENT

According to the traditional explanation of the mechanism of the fuse, the value for the cutoff current is obtained from the equation (Lipski, 1963)

$$\int_0^{t_p} i^2 \, dt = S_z^2 K \tag{1}$$

in which t_p is the pre-arcing period for the fuse, S_z the cross-section of the fuse wire in mm^2, and K a constant depending on the material used for the fuse wire (K_{Cu} = 100, 000 $amp^2 sec/m^4$).

Knowing the value of the right side of Eq. (1) as well as the dependence of current on time, one can calculate the value of the cutoff current, I_{lim}. It follows from the work of Lipski (1963) that Eq. (1) can be treated only as the first order approximation; and in spite of the large errors resulting from the approximation, Eq. (1) is useful in the design of fuses.

Equation (1), however, does not explain the dependence of the cutoff current on the length of the wire (Leonard). It has been demonstrated that shortening of the wire increases the value of the cutoff current. Also, from Eq. (1) one cannot see the observed dependence of $\int i^2 \, dt$ on the voltage used in the circuit (English Electric). By lowering the voltage to 2/3 or 1/3 of the nominal voltage, one obtains a significant decrease in the value of $\int i^2 \, dt$ with fuses of the same construction and expected currents.

An explanation of these dependences becomes simple if one accepts the content of the previous section and develops consequences of the following assumption:

"As the wire gets longer, more breaks occur in it per unit of time. Thus the limiting of the growing current occurs earlier, and the decay of the current occurs more rapidly, thereby shortening the arcing period for the fuse. The value of the integral $\int i^2 \, dt$ over the time of current flow will correspondingly decrease."

4. PROBLEM OF OVERVOLTAGE DURING THE DISINTEGRATION OF WIRE

The cause of large overvoltages during the disintegration of fuse wires is the rapid limiting of the short-circuited currents. As a result, the energy stored in the magnetic field of the circuit, $1/2\ LI^2_{lim}$, being unable to discharge through arcing gets converted into electrostatic energy $1/2\ CU^2$ (Jakubowski, 1951). Equating the two expressions for energy, one obtains the value for the overvoltage:

$$U = I_{lim}\sqrt{\frac{L}{C}}\ . \tag{2}$$

From this equation it follows that with negligible capacitances of the circuit during the action of the fuse, large voltages occur which, by the way, has been observed in practice.

As demonstrated by Baxter (1962), one can influence the magnitude of the overvoltage by appropriate choice of components for construction of a fuse. The dependence given by Baxter of overvoltages on the length of the wire, its diameter, granularity of the cooling sand, and induction of the circuit can be explained (Nasilowski, 1967) with the help of the following assumptions.

(1) Maximum value of the voltage across the fuse is proportional to the number of short arcs (Baxter, 1962) formed as a result of the disintegration of the wire into pieces.

(2) Average value of the peak voltage across a single gap cannot be greater than a constant (for copper wires in sand, it is about 50 volts).

(3) Voltage across the fuse wire stops growing when all of the energy stored in the magnetic field is used up, and the wire can no longer break up into smaller segments.

Full explanation of the curves obtained by Baxter based on the above assumptions is contained in the work of Nasilowski (1967).

5. PROBLEM OF CURRENT PAUSE

The occurrence of a current pause is not usually observed in the case of fuses. Its very occurrence would mean disqualification of the design for that fuse, and the only time that it is observed is during tests of various designs. The occurrence of current pause can be prevented by appropriate elongation of the fuse wire.

It follows from the data that the current pause observed under given conditions (U_o, d) occurs only when the length of the wire is between appropriate limits

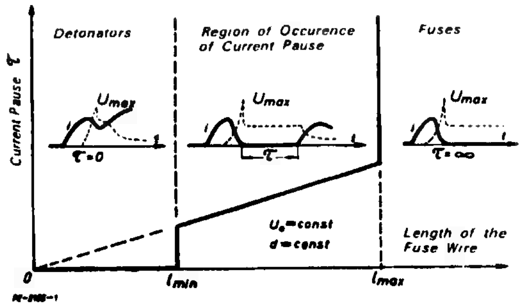

Figure 1. Regions of Practical Applications of Exploding Wires

(Figure 1). Then its time of duration is proportional to the length of the wire (Cnare and Neilson).

In the event of the current pause, an important variable is either the stabilized voltage in the circuit or the residual voltage of the capacitor (if the capacitor were used as an energy source in the experiment). When the chain of gaps in the wire does not break down under that voltage, then the current pause is infinitely long and one would be dealing with fuses.

If breakdown occurs across the gaps* during the growth of overvoltage, then the current pause has zero length. On this principle, one constructs electric detonators for rockets or any other device in which one desires almost complete discharge of a capacitor. The two regions of practical application of exploding wires are separated by the region in which the current pause has a finite value (Figure 1). Thus the study of current pause is of key value in all practical applications of exploding wires.

Figure 1 shows that the current pause is proportional to the length of the wire, and because of the regular break-up of the wire into segments (Nasilowski), it must be proportional to the number of breaks in the wire. The jump of the curve at the point ℓ_{min} indicates that a short fuse wire is unable to hold the overvoltage and gets broken by discharge. Asymptotic behavior of the curve at ℓ_{max} must follow from the fact that the probability of breakdown in a chain of gaps of sufficient length goes to zero.

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* Here, breakdown means the inability of the chain of gaps to stop the current flow.

In the case of a fuse with sand, the intense cooling of the liquid metal by the grains of sand stabilizes the arcing gaps after a radial explosion of the rest of the wire (Nasilowski), thereby increasing the resistance of individual gaps. In the case of the explosion of wire in air or in vacuum, the turbulent motion of pieces of metal in the radial direction may fill up some of the gaps, thus decreasing the resistance against breakdown of the whole chain of remaining gaps. Low pressure, which may occur in the post explosive channel along the axis of a wire (Nasilowski), may also ease the breakdown along the channel.

If one applies a hypothesis to the data (Figure 2) given by Eiselt (1952) that the length of the current pause depends on the average value of voltage across a single arcing break and then recalculates Eiselt's results (Table 1), then one obtains a family of curves (Figure 3) for different diameters of the wire rather than one "not understood" curve given in Figure 2. This agrees with results obtained by other authors studying the current pause (Chace and Moore, 1959; and Chare and Neilson).

Recalculating Eiselt's results, it was assumed that the length of subdivisions of wire is a linear function of the diameter d, of the wire (Nasilowski), and it was arbitrarily assumed that the relation is h = 5d. In reality, one still does not know the length of subdivisions for explosion of wire in air. Determination of this relation may change the numerical results of calculations, but it will not change the physical explanation and the character of the behavior of the obtained family of curves on Figure 3.

According to Eiselt, the dependence of current pause τ on the residual voltage is the same for all diameters of copper wire (Figure 2)

$$\tau = f\left(\frac{U_p}{\ell}\right) \tag{3}$$

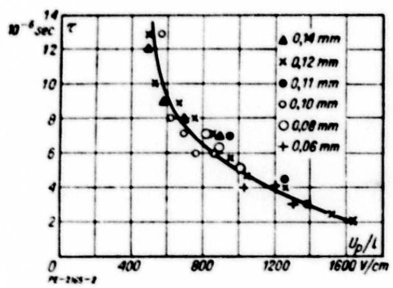

Figure 2. Eiselt's Dependence of Current Pause on the Intensity of the Residual Field, $\tau = f(U_p/\ell)$

Table 1. Recalculation of Eiselt's (1952) Result for a Single Arcing Gap, Assuming that Subdivisions are According to Relation h = 5d. Copper wires are 6 m long

Current Pause (μs)	$\frac{U_p}{\ell}$ (V/cm)	Diameter of wire d in (mm)	U_p (V)	$\frac{\ell}{h} \cong n$	$U_1 = \frac{U_p}{n}$ (V)	Symbol used on diagram
12	500	0.14	3000	86	34.9	△
9	600	0.14	3600	86	41.9	△
8	700	0.14	4200	86	48.9	△
7	900	0.14	5400	86	62.8	△
13	500	0.12	3000	100	30	X
10	550	0.12	3300	100	33	X
9	650	0.12	3900	100	39	X
8	750	0.12	4500	100	45	X
6	950	0.12	5700	100	57	X
5	1050	0.12	6300	100	63	X
4	1250	0.12	7500	100	75	X
2.4	1500	0.12	9000	100	90	X
2	1650	0.12	9900	100	99	X
7	950	0.11	5700	109	52.3	●
4.4	1250	0.11	7500	109	68.8	●
3	1375	0.11	8250	109	75.8	●
13	575	0.10	3450	120	28.8	O
8	625	0.10	3750	120	31.3	O
7	700	0.10	4200	120	35.0	O
6	750	0.10	4500	120	37.5	O
6	850	0.10	5100	120	42.5	O
7	800	0.08	4800	150	32.0	O
6.3	900	0.08	5400	150	36.0	O
5	1000	0.08	6000	150	40.0	O
4	1050	0.06	6300	200	31.5	+
4	1200	0.06	7200	200	36.0	+
3	1300	0.06	7800	200	39.0	+

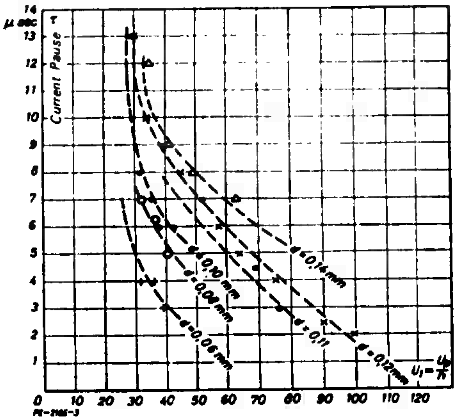

Figure 3. Eiselt's Data from Figure 2 Calculated for One Arcing Gap, Assuming that Dependence of Length of the Sub-Division is Based on h = 5d

where U_p is the residual voltage in the capacitor across the chain of gaps in the wire of length ℓ.

Experiments show that the points in Eq. (3) lie on a hyperbola (Figure 2)

$$\tau = \frac{K}{U_p/\ell} \cdot \tag{4}$$

For a fuse wire with subdivisions of length h, one can write l = nh, where n is the number of subdivisions. Thus we have

$$\tau = \frac{Kh}{U_p/n} \tag{5}$$

where U_p/n is the average value of voltage across a single gap.

Treating analogously the results of the work of one author (Nasilowski) one sees that here also there is a linear dependence of the length of a subdivision on the diameter, d, of the wire. Writing in general form h = a + bd, one obtains

$$\tau = \frac{K(a+bd)}{U_1} = K_1 + \frac{K_2 d}{U_1} \geq 0 \cdot \tag{6}$$

This kind of behavior can be observed in Figure 3.

Considering the above, one can point out the following properties of the current gap:

(1) The length of the current pause depends on the value of the voltage across the chain of gaps in the wire; that is, depends on the average voltage across a single gap.

(2) In the region of its occurrence, the current pause gets longer proportionally to the number of breaks in the wire.

(3) The current pause disappears when the chain of gaps cannot hold the growing overvoltage on the wire ($\tau = 0$).

(4) The current pause becomes infinitely long when the arcing voltage is unable to break down the chain of gaps in the fuse wire ($\tau = \infty$) .

(5) Increase of the diameter of the wire lengthens the current pause.

6. PROBLEM OF THE ABILITY OF A FUSE TO SWITCH OFF

It is intuitively obvious that the ability of a fuse to switch off the current increases with lengthening of the fuse wire; that is, by increasing the number of breaks in it. This follows from the considerations of the current pause, in particular from Figure 1.

However, lengthening of the fuse permits creation of larger overvoltages which are limited by the amount of energy stored in the magnetic field, and by linear dependence on the number of breaks in the fuse wire. Detailed analysis of the action of a fuse in breaking a short circuit is given in the work of another author (Nasilowski).

7. CONCLUSIONS

Considering the events accompanying the explosion of wire and the number of parts into which the wire breaks up, leads to a relatively simple and unified explanation of the results obtained during physical experiments and studies of fuses. This creates a possibility of working out a general theory for the process of electrical explosion of wires, which can be useful for various technological applications. Studies of exploding wires permit one to learn the properties of short arcs, treated probabilistically.

References

Barrington, A. E. (1956) The fusing of wires with heavy surge currents, Brit. J. Appl. Phys. 7:408.

Baxter, H. W. (1962) Electric Fuses, London, E. Arnold.

Chace, W.G. and Moore, H.K. (1959), Exploding Wires, Plenum Press, Vol. 1, 1959; Vol. 2, 1962; Vol. 3, 1964.

Cnare, E.C., Neilson, F.W. Large exploding wires - correlation to small wires and pause time versus length dependency, Exploding Wires, Vol. 1.

Eiselt, B. (1952) Über den Ablauf von Drahtexplosionen (On the Course of Wire explosions) Z. Physik 132:54.

English Electric, H.R.C. Cartridge fuse links type GS for the protection of semiconductor rectifiers, Catalog FG/189.

Hrynczuk, J., Theory of Magneto-thermo-elastic mechanism for exploding wires subjected to high currents, Inst. Maszyn Przeplywowych P.A.N. Gdansk, Bulletin No. 390.

Jakubowski, J.L. (1951) High Voltage Technology, Warsaw.

Keilhacker, M., (1960) Über den Mechanismus der explosionartigen Verdampfung von Kupferdrähten (On the mechanism of explosive evaporation of copper wires) Z. Physik 12:49.

Kvartskhava, I. F. et al (1956) Oscillographic determination of energy of electrically exploded wires, ZETF 31:745.

Leonard, H.S., Effect of bridgewire parameters or explosive initiation, Exploding Wires, Vol. 3.

Lipski, T. (1963) Graphical method for determination of cutoff currents in fuses, Prz. Elektrotech 3:101.

Lipski, T. (1964) Post arcing currents in fuses with sand, Prz. Elektrotech 1:17

References

Lucchi, I. (1949) La constante d'inertia termica dei fusibili (The thermal constant of inertia of fusion), L'Elettrotecnica 36:142.

Nasilowski, J., Unduloids and striated disintegration of wires, Exploding Wires, Vol. 3.

Nasilowski, J. (1961) Phenomena associated with disintegration of conductors overloaded by short circuited currents, Prz. Elektrotech 10:397.

Nasilowski, J. (1967) Overcharges and overvoltages during short circuits in D.C. networks protected by fuses, Arch. Elektrotech (No. 3).

Nasilowski, J. (1964) Process of breaking of short circuits by fuses, Prz. Elektrotech 1:21.

Wrana, J., 1939: Vorgange beim Schmelzen und Verdampfen von Drahten mit sehr hohen Stromdichten (Melting and evaporation processes in wires at high current densities), Arch. Elektrotech 33:656.

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